PHASED ARRAY RADIOMETER CALIBRATION USING A RADIATED NOISE SOURCE

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1. INTRODUCTION

Electronic beam steering capability of phased array antenna systems offer significant advantages when used in real aperture imaging radiometers. The sensitivity of such systems is limited by the ability to accurately calibrate variations in the antenna circuit characteristics. Passive antenna systems, which require mechanical rotation to scan the beam, have stable characteristics and the noise figure of the antenna can be characterized with knowledge of its physical temperature [1],[2]. Phased array antenna systems provide the ability to electronically steer the beam in any desired direction. Such antennas make use of active components (amplifiers, phase shifters) to provide electronic scanning capability while maintaining a low antenna noise figure. The gain fluctuations in the active components can be significant, resulting in substantial calibration difficulties [3]. In this paper, we introduce two novel calibration techniques that provide an end-to-end calibration of a real-aperture, phased array radiometer system. Empirical data will be shown to illustrate the performance of both methods.

2. ONE DIODE TECHNIQUE

Fig 1 shows a simplified block diagram of a two load radiometer system [4] with a phased array antenna array. Fig 2 shows the configuration of each active antenna element and the center element of the array. The center element of the array radiates a Gaussian noise of known amplitude. A controller steps the radiometer between target scene observations (with the radiated source turned off), internal load observations and an observation of the target scene with the radiated noise source turned on. The difference between the emission temperature measured with the noise source turned on and off provides a method to compute the gain of the antenna electronics. Though the plane of reference for the calibration is the front-end of the radiometer, this technique can account for drifts in the gain of the antenna electronics, thus providing a quasi- end-to-end calibration.

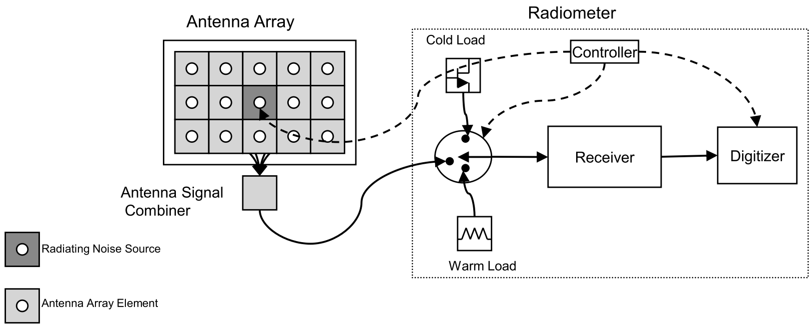
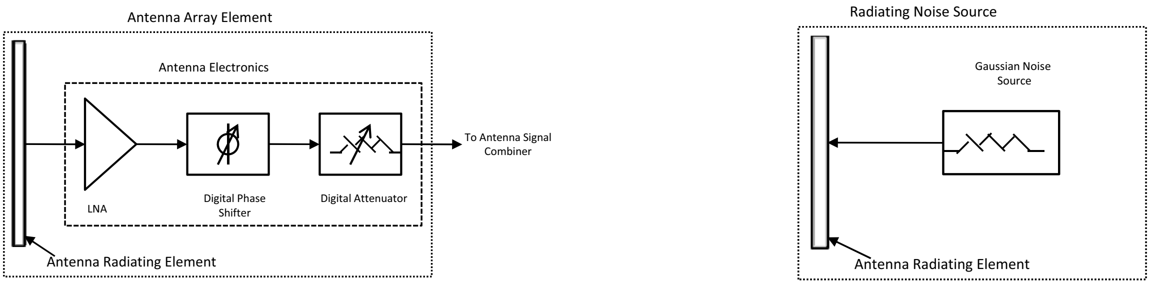


Fig. 1. Simplified block diagram of a radiometer system incorporating the one diode technique



(a) Active antenna element

(b) Center element

Fig. 2. Configuration of the antenna electronics

3. TWO DIODE TECHNIQUE

Fig 3 shows a modified radiometer and antenna array system. The individual active antenna element is modified from the one diode method to include a front-end RF switch on each antenna element as illustrated in fig 4. The center element of the array is the same as the one diode method. In this setup, the two internal loads in the radiometer are replaced by a noise source injected directly into the antenna array through a feed network. The controller now steps between the target scene observation (with the radiated noise source turned off), an observation of the target scene with the radiated noise source turned on and the injected load. In this method, the plane of reference for the calibration is the antenna itself, providing an complete end-to-end calibration.

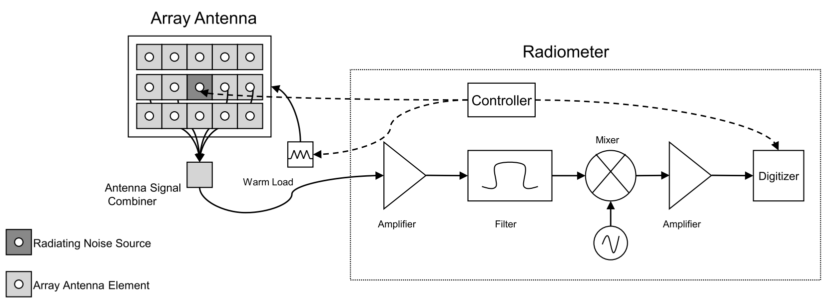


Fig. 3. Simplified block diagram of a radiometer system incorporating the two diode technique

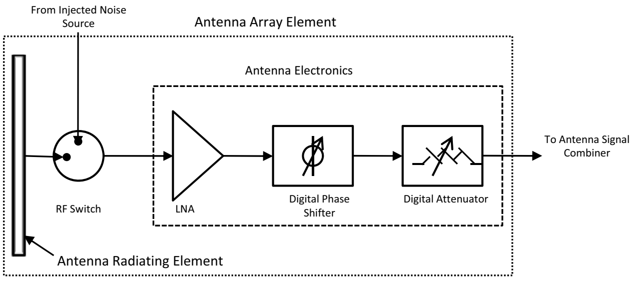


Fig. 4. Configuration of the antenna electronics

4. CONCLUSION

This paper presents two novel methods to calibrate real-aperture microwave radiometer systems with phased array antennas. The proposed techniques make use of mutual coupling between antenna elements to measure the instantaneous gain of the antenna electronics. The one diode technique uses three calibration loads (one radiated antenna load and two loads internal to the radiometer) to compute the gain of the antenna electronics and the receiver while using the radiometer input as the calibration plane of reference. The two diode method uses only two calibration loads (one load is radiated from the antenna and the second load is injected into the antenna electronics) to obtain the overall system gain. The plane of reference for this method is the input to the antenna. The performance benefits of the two methods will be shown using empirical results.

5. REFERENCES

[1] C. Ruf, S. Keihm, and M. Janssen, "Topex/poseidon microwave radiometer (tmr). i. instrument description and antenna temperature calibration," *Geoscience and Remote Sensing, IEEE Transactions on*, vol. 33, no. 1, pp. 125–137, Jan 1995.

[2] T. Jackson, R. Bindlish, A. Gasiewski, B. Stankov, M. Klein, E. Njoku, D. Bosch, T. Coleman, C. Laymon, and P. Starks, "Polarimetric scanning radiometer c and x band microwave observations during smex03," in *Geoscience and Remote Sensing Symposium, 2004. IGARSS '04. Proceedings. 2004 IEEE International*, vol. 1, Sept. 2004, pp. –324.

[3] H. Schuman, "Phased array antenna design considerations for large aperture microwave radiometer earth observations," in *Antennas and Propagation Society International Symposium, 1993. AP-S. Digest*, Jun- 2 Jul 1993, pp. 720–723 vol.2.

[4] M. Goodberlet and J. Mead, "Two-load radiometer precision and accuracy," *Geoscience and Remote Sensing, IEEE Transactions on*, vol. 44, no. 1, pp. 58–67, Jan. 2006.

Phased Array Radiometer Calibration Using a Radiated Noise Source

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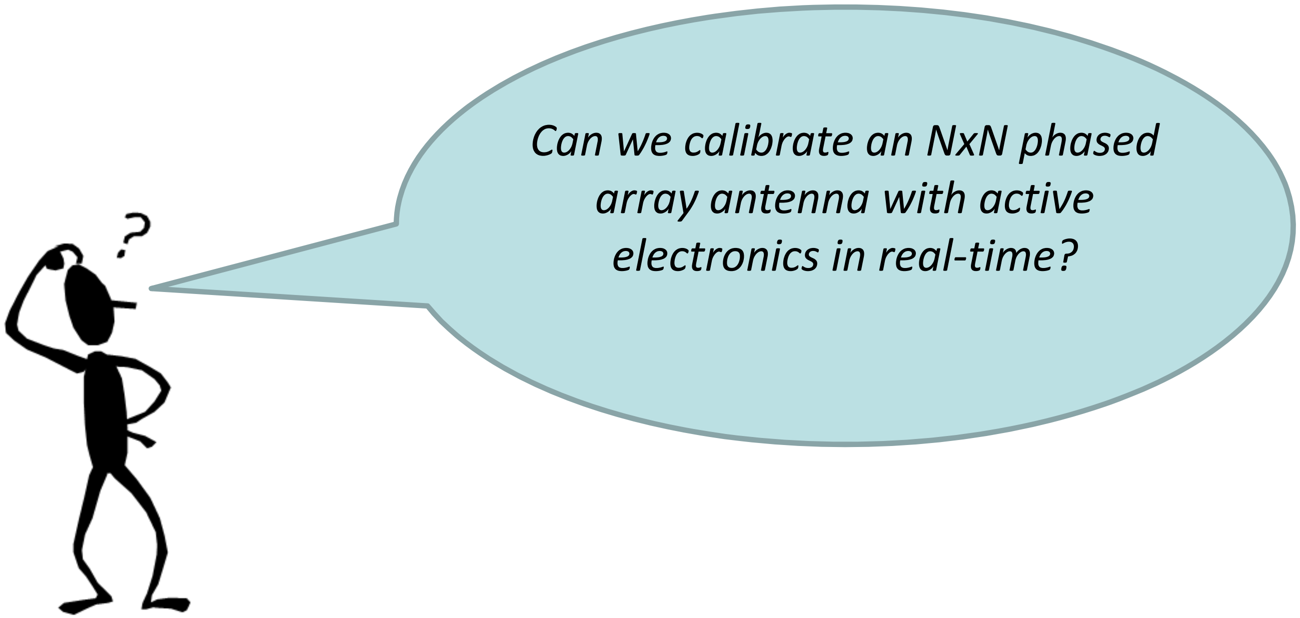
Motivation

- Passive real-aperture microwave remote sensing systems have predominantly been ‘staring’ or mechanically steered systems.

- Phased arrays have been used for years in radar systems for electronic beamsteering but present enormous calibration challenges in passive systems



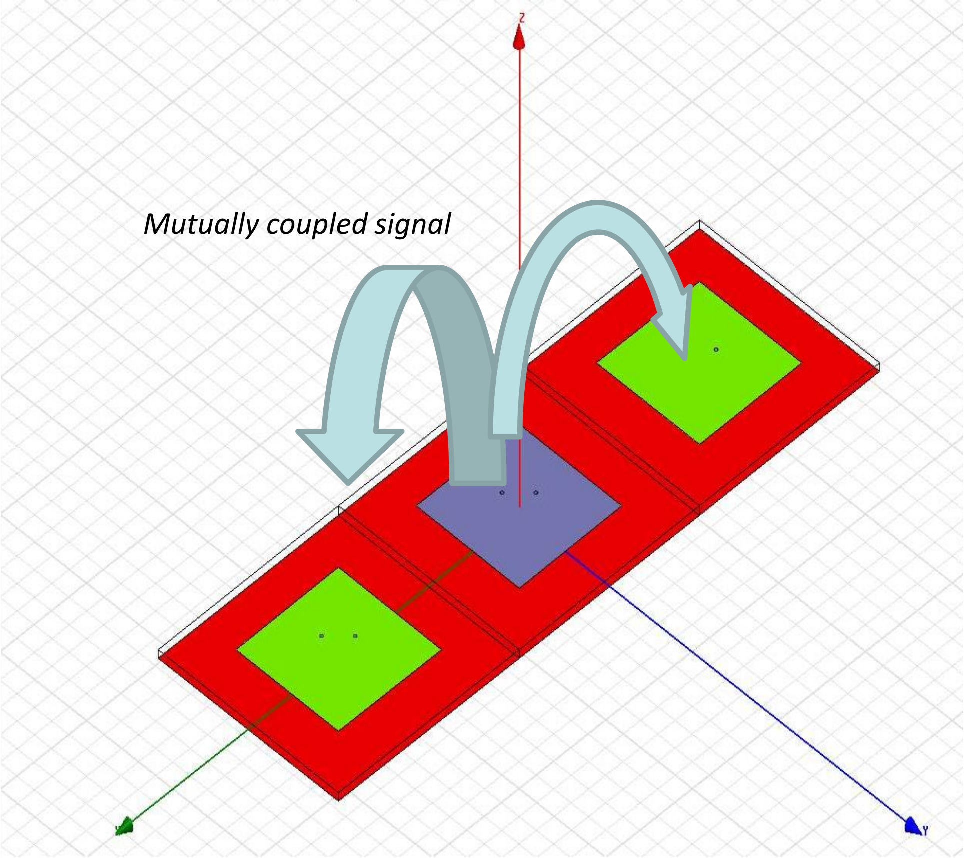
Motivation

CHALLENGES

- The gain of active RF components can vary with time – short term (minutes) drift, component ageing.
- The noise figure can be expected to be fairly stable at least in the short term.

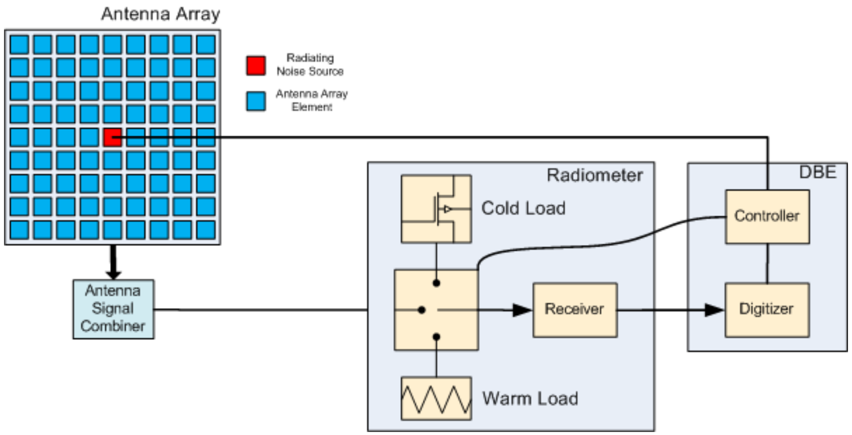
SOLUTION

- Calibrate the antenna by observing a known source
    - Place a noise source in the field of view of the antenna
    - Use an injected noise source
    - Use a mirror to look at a cold sky target
    - Use mutual coupling between antenna elements to establish a calibration source



One Diode Calibration Method

Motivation: <u>In-flight real-time continuous calibration</u>

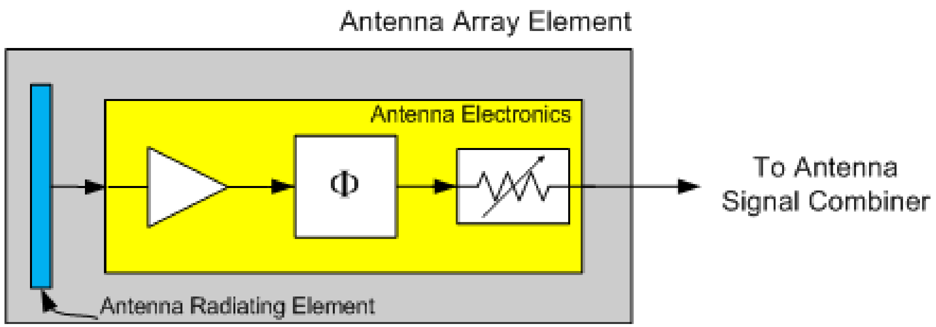


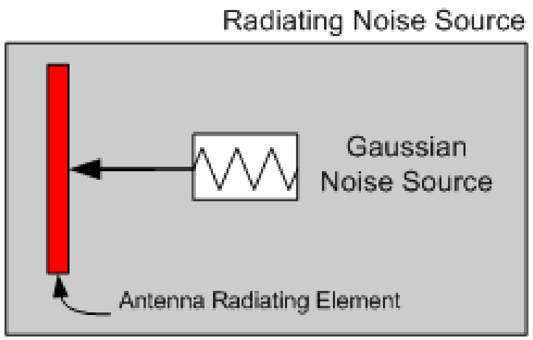
Features:

- One Antenna Diode Calibration
- Measure antenna electronics gain in real time
- Utilize mutual coupling between antenna elements as a calibration source
- Calibrate every scan angle in real time

Implementation:

- Radiate a noise source from the center element of the array
- Radiated Diode (ENR = 40 dB) used with a Hach radiometer





One Diode Method

Calibration Equations

$$\overline{P}_w = kBG_r(T_w + T_r)$$

$$\overline{P}_c = kBG_r(T_c + T_r)$$

$$\overline{P}_s = kBG_r(G_a(T_A + T_{ae}) + T_r)$$

$$\overline{P}_D = kBG_r(G_a(T_A + T_{ae} + T_D) + T_r)$$

$$\gamma_{1D} = \frac{\hat{P}_s - \hat{P}_c}{\hat{P}_D - \hat{P}_s} = \frac{\hat{G}_a(\hat{T}_A + T_{ae}) - T_c}{\hat{G}_a T_D}$$

$$\hat{T}_A = T_D\gamma_{1D} + \frac{T_c}{\hat{G}_a} - T_{ae}$$

P_w – Power observed from the radiometer warm load at noise temperature T_w
P_C – Power observed from the radiometer cold load at noise temperature T_c
P_S – Power observed from the target scene (radiated diode off)
P_D – Power observed from the target scene with the radiated diode (T_D) on
k – Boltzmann's constant
G_r – Radiometer gain
G_a – Antenna electronics gain
T_r – Radiometer noise temperature
T_{ae} – Antenna noise temperature

$$\hat{G}_a = \frac{\hat{P}_D - \hat{P}_s}{\hat{P}_w - \hat{P}_c} \cdot \frac{T_w - T_c}{T_D}$$

Measurement Precision

$$\Delta T_A = \underbrace{\Delta\gamma_{1D}.\frac{\partial T_A}{\partial \gamma_{1D}}}_{\text{Error in }\gamma} + \underbrace{\Delta G_a.\frac{\partial T_A}{\partial G_a}}_{\text{Error in }G_a}$$

$$\Delta\gamma_{1D}.\frac{\partial T_A}{\partial \gamma_{1D}} = \sqrt{\frac{a_c^2}{\tau_c} + \frac{a_s^2}{\tau_s} + \frac{a_D^2}{\tau_D}}$$

$$\Delta G_a.\frac{\partial T_A}{\partial G_a} = \sqrt{\frac{a_{gD}^2}{\tau_D} + \frac{a_{gs}^2}{\tau_s} + \frac{a_{gw}^2}{\tau_w} + \frac{a_{gc}^2}{\tau_c}}$$

$$a_c = \frac{T_c + T_r}{G_a\sqrt{B}}$$

$$a_s = \frac{(G_a T_A + T_r).(G_a(T_A + T_D) - T_c)}{T_D G_a^2\sqrt{B}}$$

$$a_D = \frac{(G_a(T_A + T_D) + T_r).(G_a T_A - T_c)}{T_D G_a^2\sqrt{B}}$$

$$a_{gD} = \frac{T_c.(G_a(T_A + T_{ae} + T_D) + T_r)}{T_D G_a^2\sqrt{B}}$$

$$a_{gs} = \frac{T_c.(G_a(T_A + T_{ae}) + T_r)}{T_D G_a^2\sqrt{B}}$$

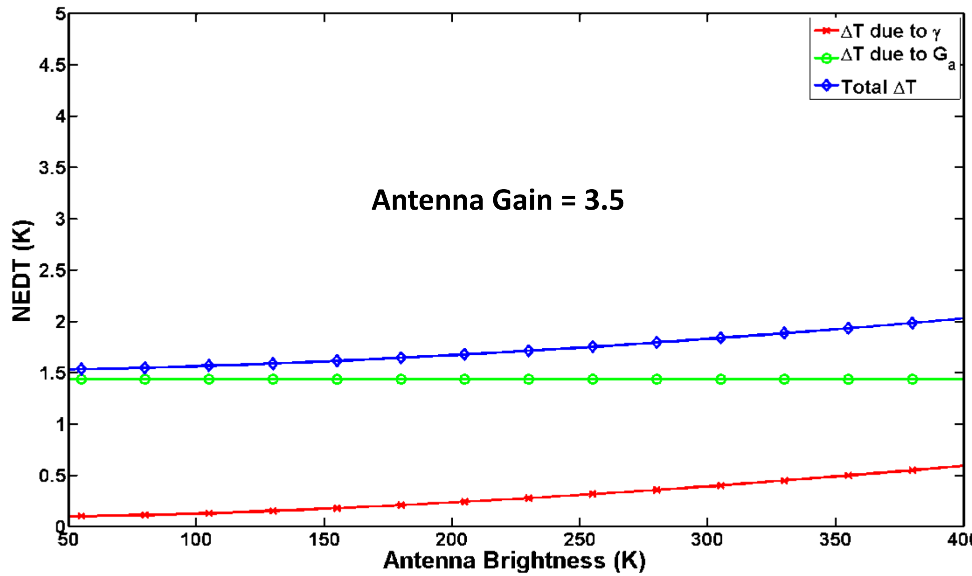
$$a_{gw} = \frac{T_c.((T_c + T_w).(T_w + T_r))}{G_a\sqrt{B}.(T_w - T_c)^2}$$

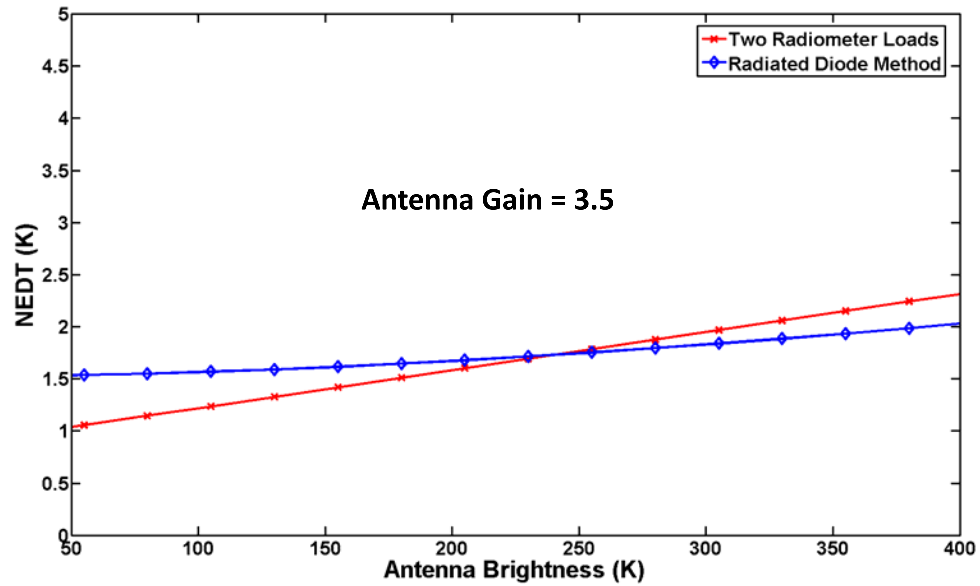
$$a_{gc} = \frac{T_c.((T_c + T_w).(T_c + T_r))}{G_a\sqrt{B}.(T_w - T_c)^2}$$

$$\tau = \tau_w + \tau_c + \tau_s + \tau_D$$

Measurement Precision

Receiver Noise Temperature	400 K
Pre-detection Bandwidth	24 MHz
Antenna Noise Temperature	300 K
Total Dwell Time	1 sec
Radiometer Warm Load	300K
Radiometer Cold Load	210K
Antenna Radiated Diode	300K





(1) Two radiometer loads – Goodberlet et al, 2006

(2) Two Diode method

Two Diode Calibration Method

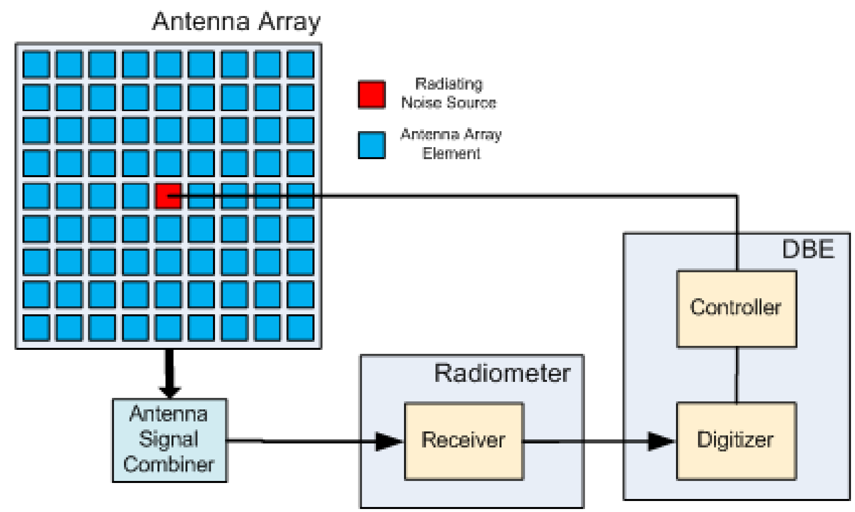
Motivation: <u>In-flight real-time continuous calibration</u>

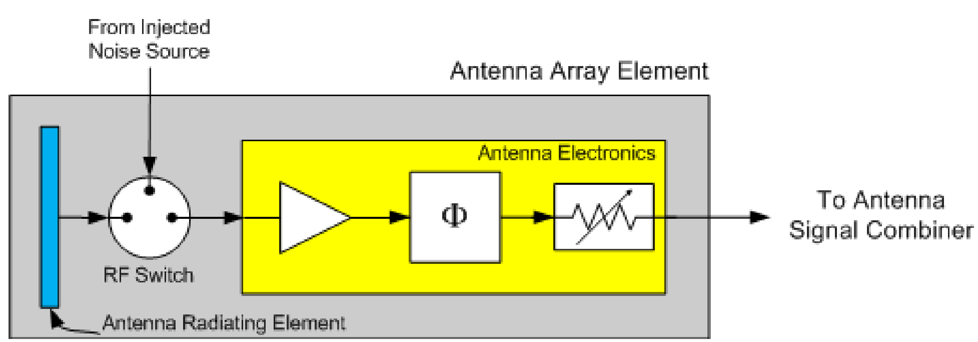
Features:

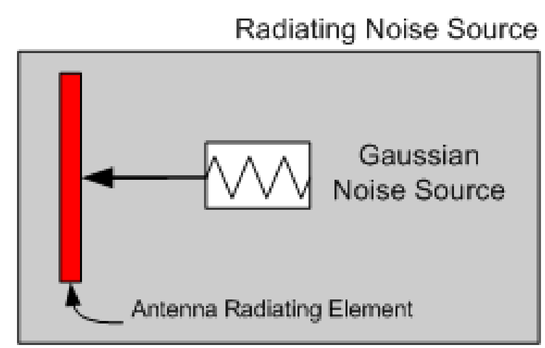
- Two Diode Calibration
- End-to-end calibration for a phased array system
- Calibrate every scan angle in real time
- Utilize mutual coupling between antenna elements as a calibration source
- Requires fewer calibration loads than the One Diode Method

Implementation:

- Radiate a noise source from the center element of the array
- Radiated Diode (ENR = 40 dB) and an injected noise source (~300 K)







Two Diode Method

Calibration Equations

$$\overline{P_i} = kBG_r(G_a(T_i + T_{ae}) + T_r)$$

$$\overline{P_s} = kBG_r(G_a(T_A + T_{ae}) + T_r)$$

$$\overline{P_D} = kBG_r(G_a(T_A + T_{ae} + T_D) + T_r)$$

$$\gamma_{2D} = \frac{\hat{P}_i - \hat{P}_s}{\hat{P}_i - \hat{P}_s} = \frac{(T_i + \hat{T}_A)}{T_i - (\hat{T}_A + T_D)}$$

$$\hat{T}_A = T_i + T_D \cdot \left(\frac{\gamma_{2D}}{1 - \gamma_{2D}} \right)$$

Independent of system parameters!

P_i – Power observed from the injected noise source at noise temperature T_i
P_S – Power observed from the target scene (radiated diode off)
P_D – Power observed from the target scene with the radiated diode (T_D) on
k – Boltzmann's constant
G_r – Radiometer gain
G_a – Antenna electronics gain
T_r – Radiometer noise temperature
T_{ae} – Antenna noise temperature

Measurement Precision

$$\Delta T_A = \Delta\gamma_{2D} \cdot \frac{\partial T_A}{\partial \gamma_{2D}}$$

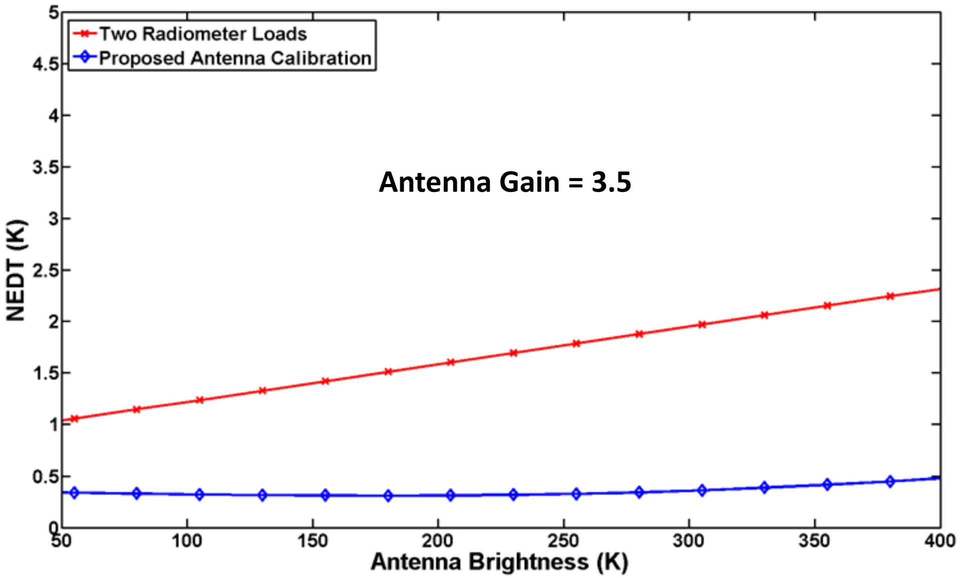
$$\Delta\gamma_{2D} \cdot \frac{\partial T_A}{\partial \gamma_{2D}} = \sqrt{\frac{a_i^2}{\tau_i} + \frac{a_s^2}{\tau_s} + \frac{a_D^2}{\tau_D}}$$

$$a_i = \frac{G_a T_i + T_r}{G_a \sqrt{B}}$$

$$a_s = \frac{(G_a T_A + T_r).(T_i - T_A - T_D)}{T_D G_a \sqrt{B}}$$

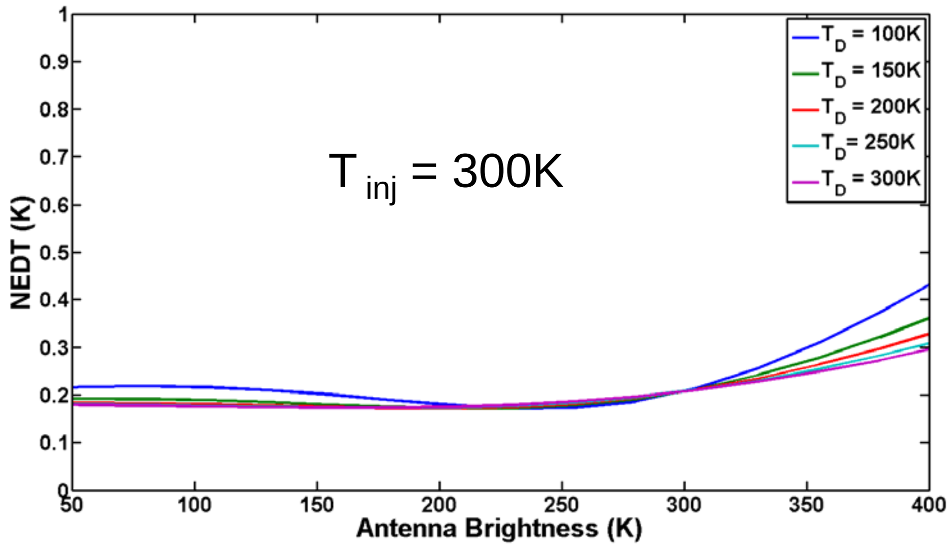
$$a_D = \frac{(G_a(T_A + T_D) + T_r).(T_A - T_i)}{T_D G_a \sqrt{B}}$$

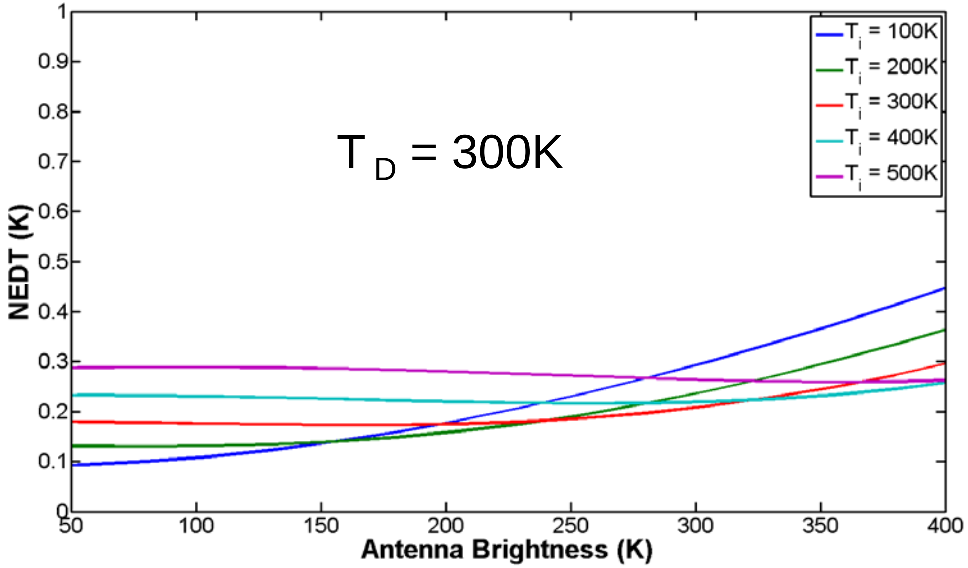
$$\tau = \tau_i + \tau_s + \tau_D$$



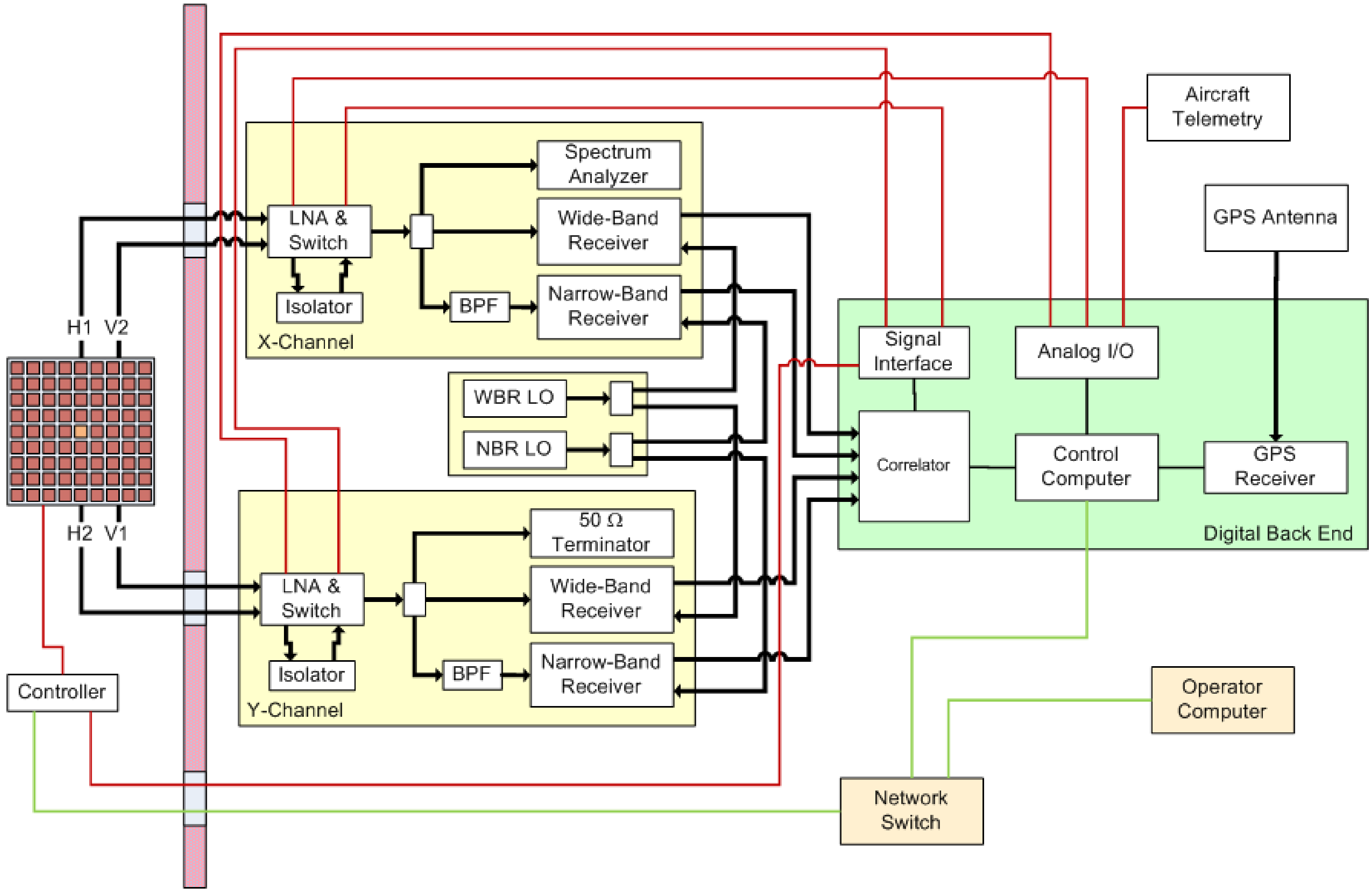
Receiver Noise Temperature	400 K
Pre-detection Bandwidth	24 MHz
Antenna Noise Temperature	300 K
Total Dwell Time	1 sec
Antenna Injected Load	300K
Antenna Radiated Diode	300K

Measurement Precision





MAPIR System Architecture



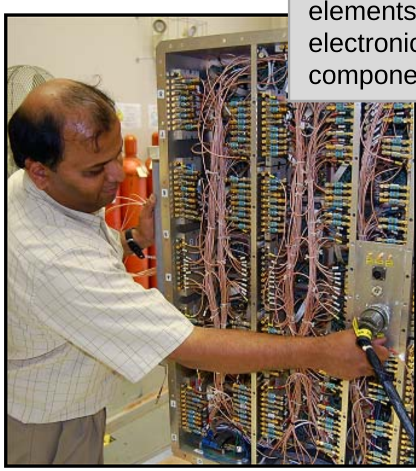
Phased Array Antenna

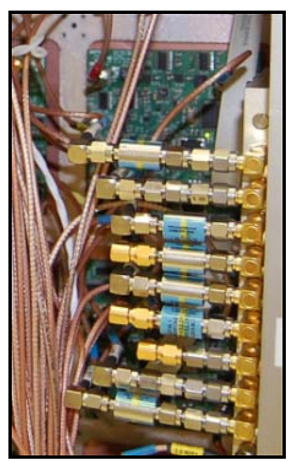
MSFC SCIENCE & MISSION SYSTEMS

Frequency	L- band (2 passbands)
Antenna Type	Real aperture planar phased array
Array	81 element (9x9) electronic beam steering
Dimensions	102 x 102 x 18 cm
Beamwidth	15° (3dB at nadir)
Polarizations	Horizontal, Vertical
Beams	2 simultaneous acquisition
Scan Type	Push-broom, Conical, Staring at any angle
Control	In-flight reprogrammable scan mode
Electronics	Programmable Integrated circuit (PIC)

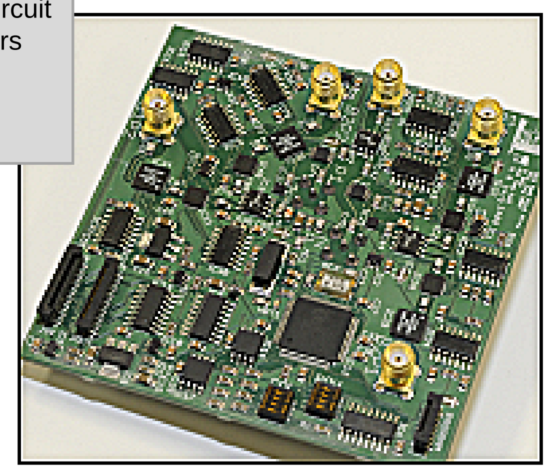
The front side comprises passive antenna elements.

Behind the antenna elements are the electronic control components.





Each antenna element has a circuit board that steers the beam and switches RF polarization.

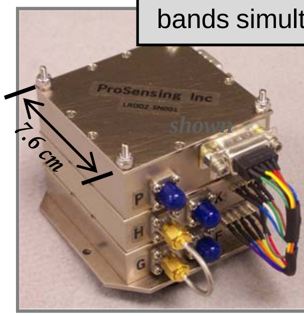


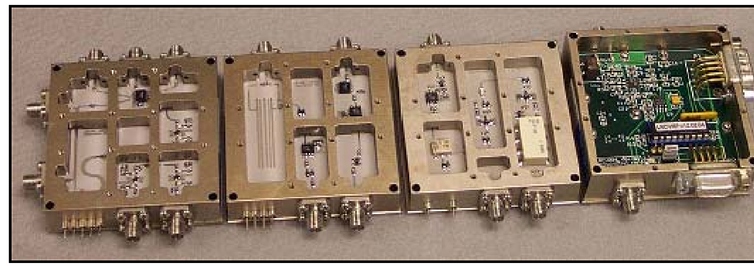
Receivers

Type	Hach
No. Channels	4
Array	81 element (9x9) electronic beam steering

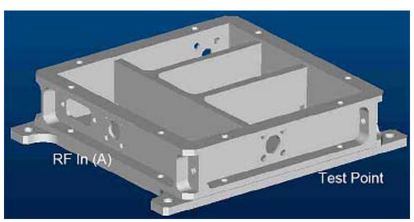
	Narrow	Wide
No. Receivers	2	2
Antenna Inputs	2	2
Passbands	1401-1425 MHz	1350-1450 MHz
Integration Time	10 ms (min.)	10 ms (min.)
Dimensions	7.6 x 7.6 x 7.6 cm	8.9 x 8.9 x 3.8 cm
Internal Cal. Loads	Warm: 300 K Cold: 150 K	Warm: 300 K Cold: 150 K
Down Convert Freq.	8-32MHz	10-110 MHz

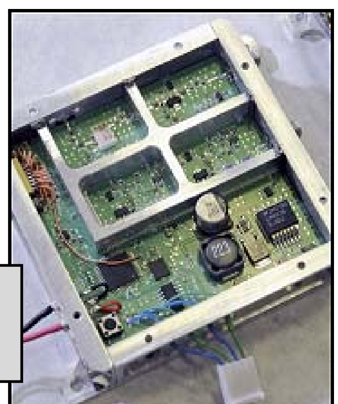
Four receivers acquire data at two narrow bands and two wide bands simultaneously.





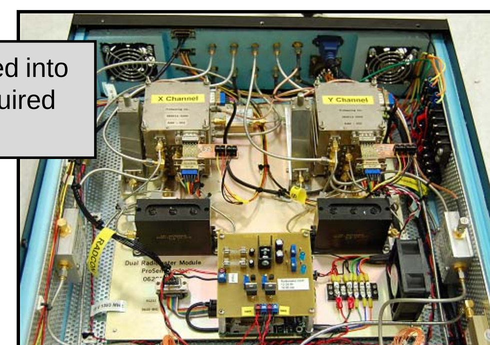
PROSENSING





The wide band receivers developed in-house observe a wider spectrum for possible RFI that may effect observations.

All four receivers are integrated into a common enclosure with required splitters, filters and amplifiers.



Theses radiometers are a byproduct of a Phase I and Phase II SBIR

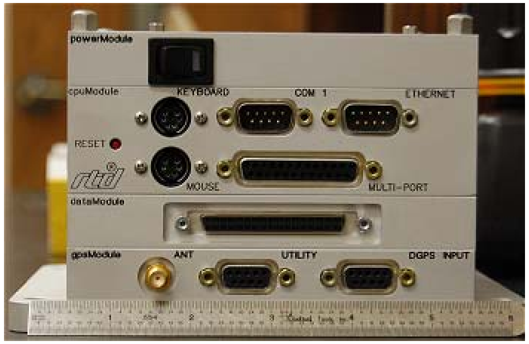
Correlator & Digital Back End

Dimensions	48 cm x 69 cm x 22 cm
Filters	16 subbands for each channel
Subchannel Bandwidth	2.65 MHz (narrowband receiver) 7.8 MHz (wideband receiver)
Clock	10 ms oscillator
Digitizer	12 bit ADC; internal processing to 7 bit
Correlator	Nallatech BenADC-V4 with Xilinx FPGA
RFI Processing	ADD method: Computes I & Q moments
Control	RTD PC/104-*Plus* stack
Storage	11 Mb packets

Subband	Center Freq. (MHz)	
Number	Narrow	Wide
1	1401.7	1338.9
2	1403.2	1346.7
3	1404.7	1354.5
4	1406.3	1362.3
5	1407.8	1370.2
6	1409.4	1378.0
7	1411.0	1385.8
8	1412.5	1393.6
9	1414.1	1401.4
10	1415.7	1409.2
11	1417.2	1417.0
12	1418.8	1424.8
13	1420.3	1432.7
14	1421.9	1440.5
15	1423.5	1448.3
16	1424.6	1456.1

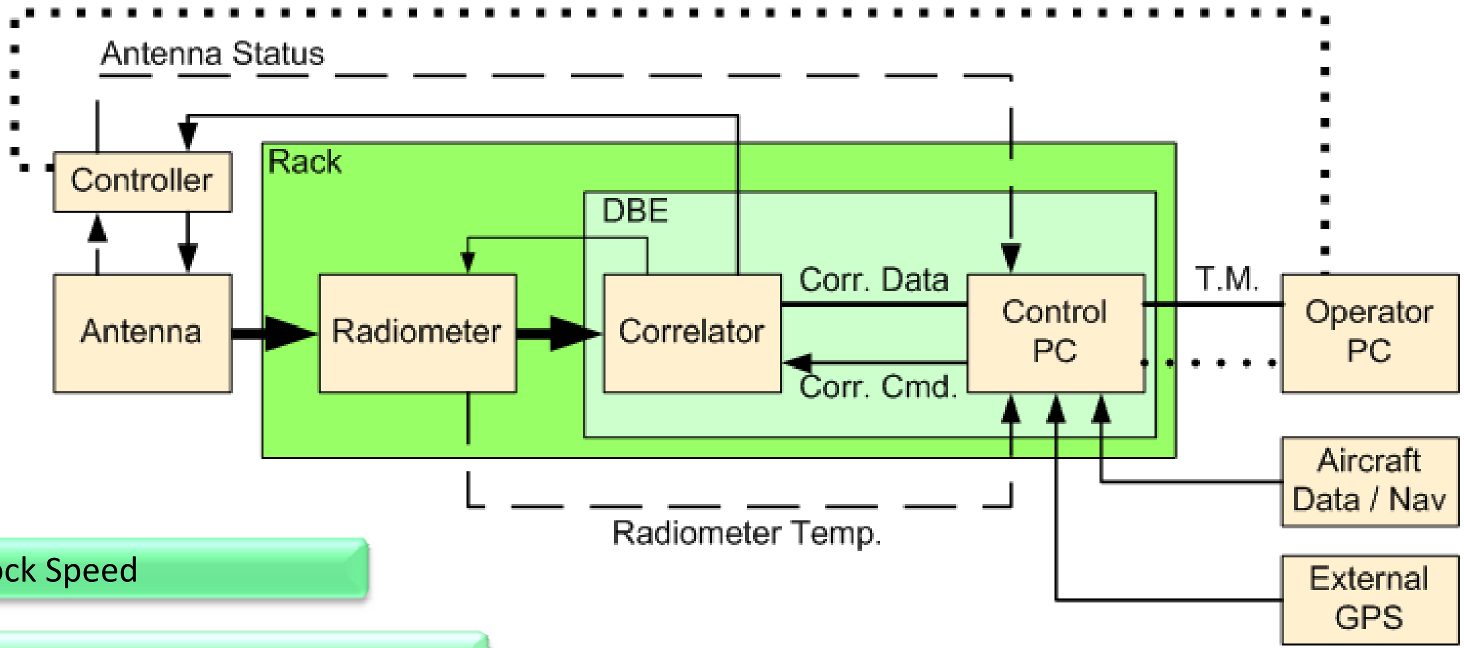
Correlator Module:
Nallatech BenADC-V4 firmware with Xilinx Spartan FPGA

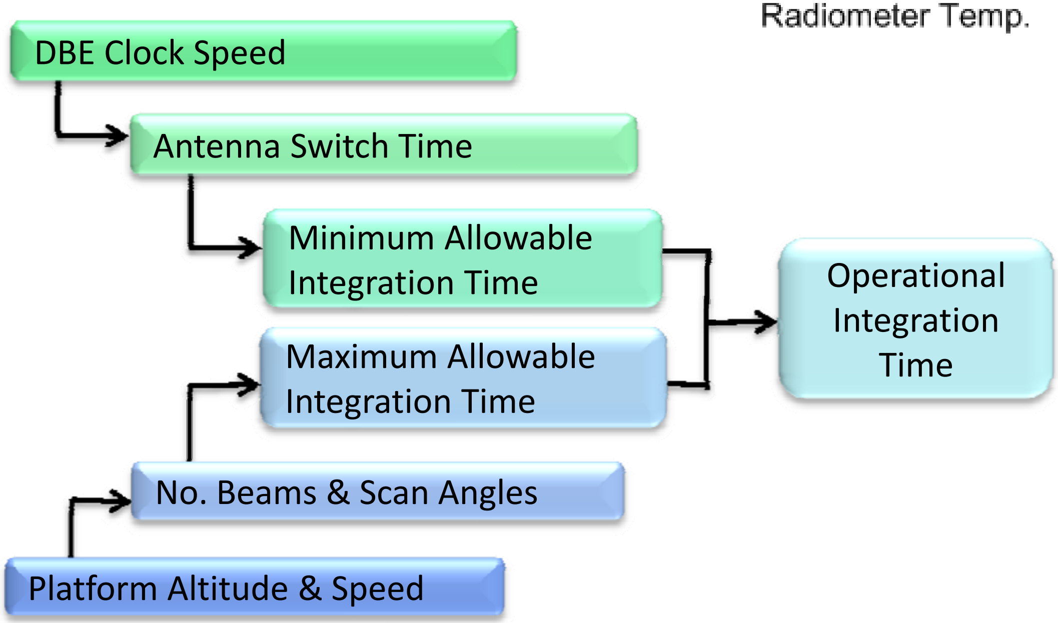
Control Computer:
RTD PC/104-*Plus* Stack

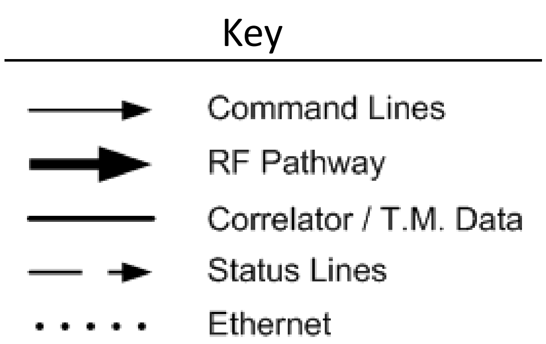


Developed by Univ. of Michigan, Space Physics Research Lab

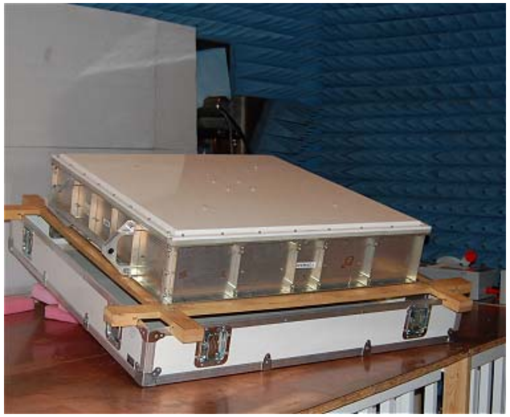
Command and Control





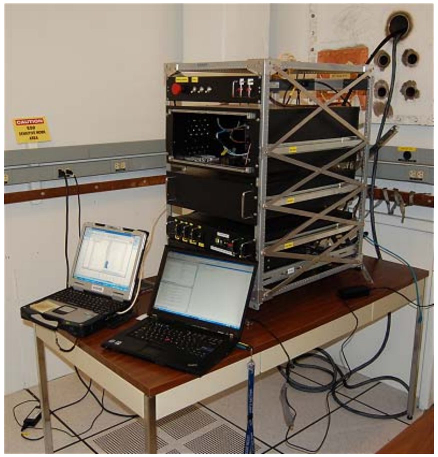


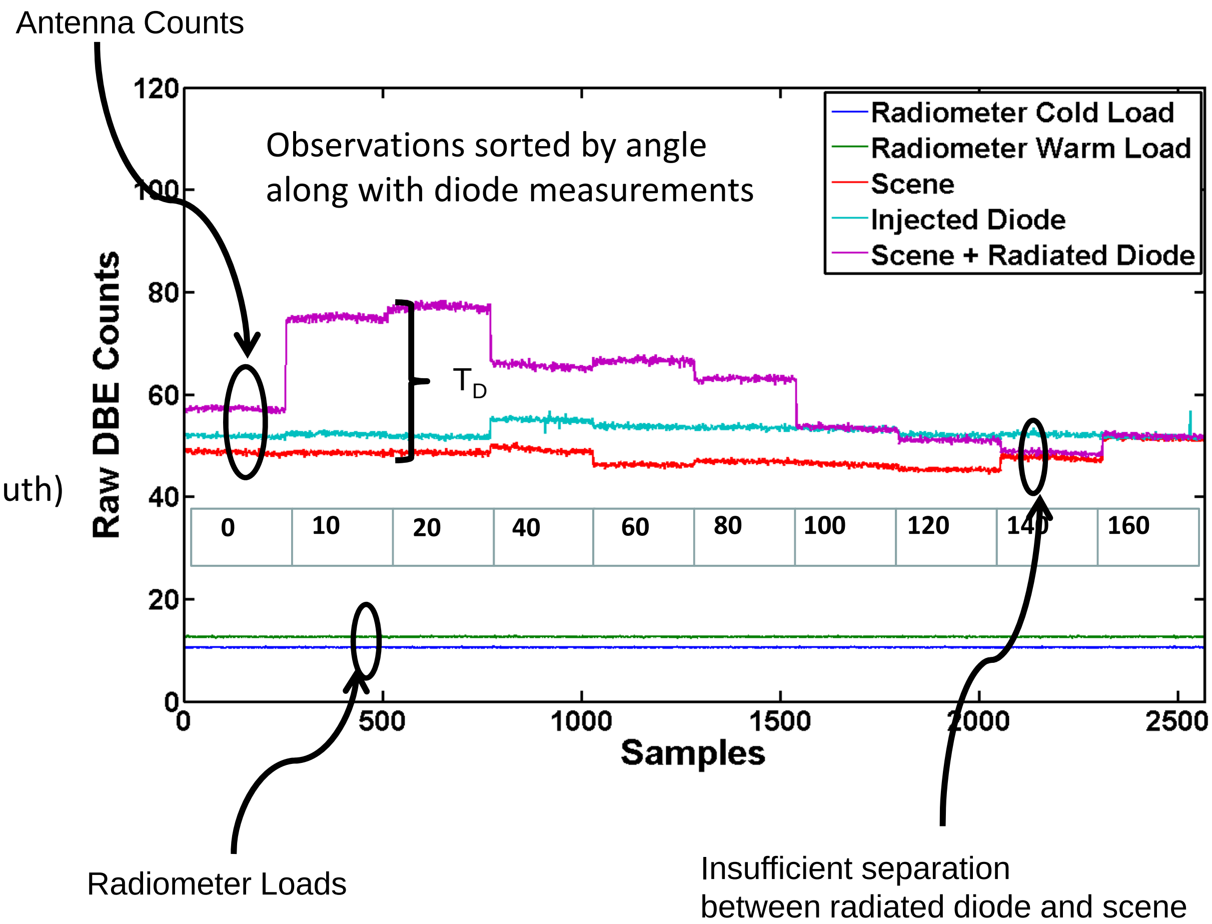
Calibration Performance Evaluation



Experimental Set-up

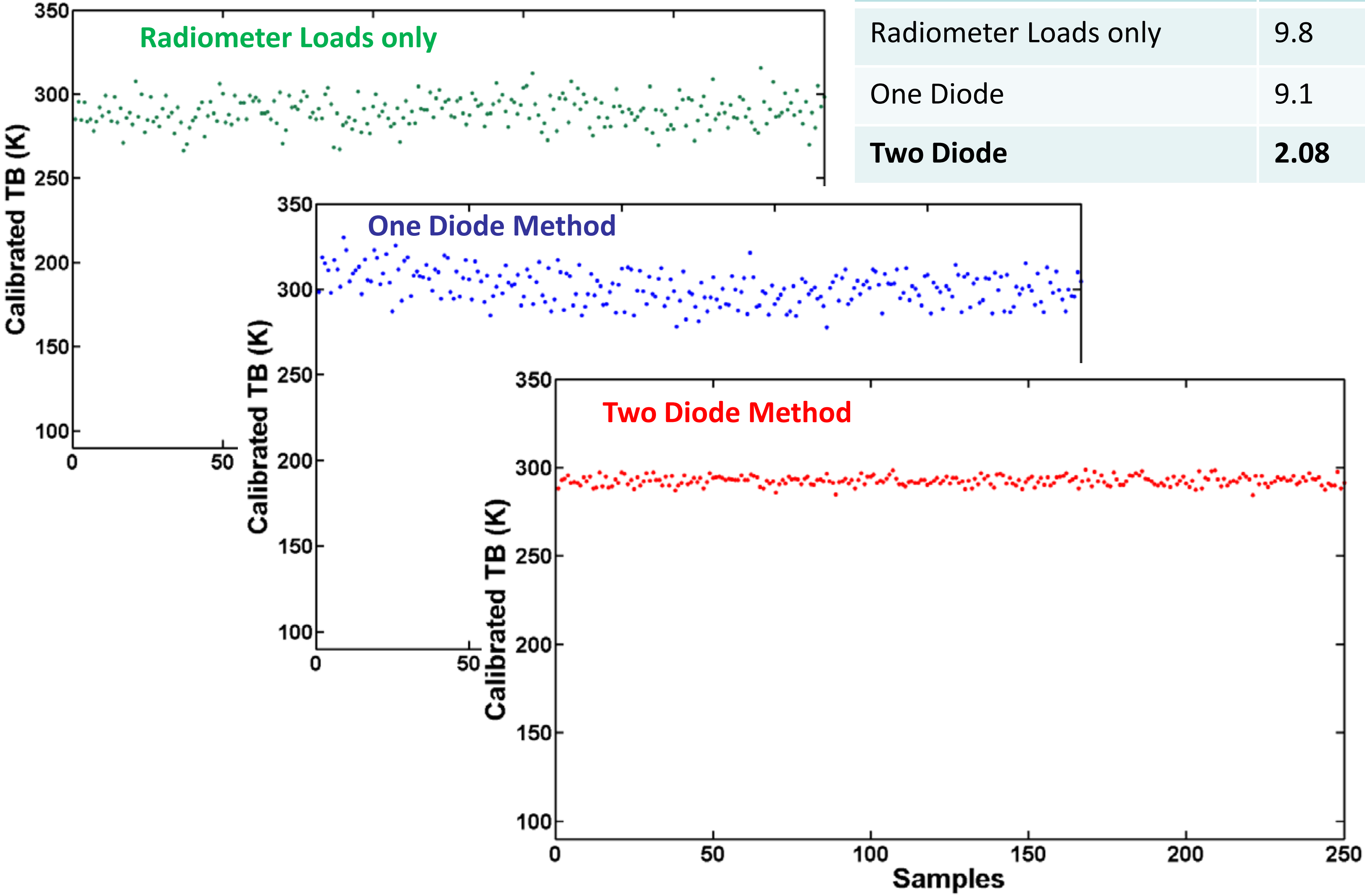
- NASA EMI chamber
- Antenna on table looking at ceiling
- Scanning forward half only (0-160° azimuth) in 20° increments at 40° look angle
- Control system in adjoining room





Performance Evaluation

Cal Method	NEDT @10ms	Meas Std Dev
Radiometer Loads only	9.8	9.87
One Diode	9.1	9.74
Two Diode	**2.08**	**2.67**



Challenges

- The amplitude of the mutually coupled signal is a function of scan angle – results in different radiated diode observations at each scan angle
- Impact of the difference in system noise temperature due to front-end antenna switch loss as a function of switch position
- Efficiency of the radiated diode as a function of antenna size? Can this be overcome by using multiple radiating elements embedded within the array?

Conclusions & Future Work

Conclusions

- Use of a radiated noise diode as a calibration source for an antenna array can be (relatively) simple to implement and significant applications
- First results are promising and indicate good potential for beam forming radiometers
- Opportunities for improvement

Future Work

- Address scan angle dependent mutual coupling issues
- Analyze efficiency of calibration as a function of antenna size
- Improve the injected feed network

Questions